DOCUMENT RESUME

ED 406 405 TM 026 287

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TITLE	Alpha-Max: A Novel New Multiple Comparison Procedure.
PUB DATE	Nov 96
NOTE	37p.; Paper presented at the Annual Meeting of the Mid-South Educational Research Association (Tuscaloosa, AL, November 6-8, 1996).
PUB TYPE	Reports - Evaluative/Feasibility (142) -- Speeches/Conference Papers (150)
EDRS PRICE	MF01/PC02 Plus Postage.
DESCRIPTORS	*Comparative Analysis; *Statistical Significance
IDENTIFIERS	*Bonferroni Procedure; Multiple Comparisons

ABSTRACT

Alpha-Max is a multiple comparison procedure that is based on the Bonferroni inequality. However, rather than using preset adjusted alpha values for each pairwise contrast, Alpha-Max bases the decisions on the actual p-values for the pairwise contrasts. After a significant omnibus F-test, the pairwise p-values are determined and ordered from lowest to highest. Alpha-Max includes as being significant only those contrasts whose sum of sequential additive p-values is less than the nominal alpha desired. Results for Alpha-Max are compared with results using the original Bonferroni, Tukey's Honestly Significant Difference Procedure (HSD), and Student-Newman-Keuls procedures based on simulated three- and four-group data sets with varying mean patterns and sample sizes. In every case, Alpha-Max had more power to detect pairwise differences as compared with Bonferroni and HSD and in one mean pattern was more powerful than SNK in detecting mean differences at r=K-1 steps. Needed additional research and possible applications of this procedure are discussed. (Contains 15 tables and 24 references.) (Author/SLD)

ALPHA-MAX:

A NOVEL NEW MULTIPLE COMPARISON PROCEDURE

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Presented at the Annual Meeting of the
Mid-South Educational Research Association
Tuscaloosa, Alabama
November 6-8, 1996

Abstract

Alpha-Max is a multiple comparison procedure which is based on the Bonferroni inequality. However, rather than using pre-set adjusted alpha values for each pairwise contrast, Alpha-Max bases the decisions on the actual p-values for the pairwise contrasts. After a significant omnibus F test, the pairwise p-values are determined and ordered from lowest to highest. Alpha-Max includes as being significant only those contrasts whose sum of sequential additive p-values is less than the nominal alpha desired. Results for Alpha-Max are compared with results using the original Bonferroni, Tukey's HSD, and Student-Newman-Keuls (SNK) procedures based on simulated three and four-group data sets with varying mean patterns and sample sizes. In every case, Alpha-Max had more power to detect pairwise differences as compared with Bonferroni and HSD and in one mean pattern was more powerful than SNK in detecting mean differences at r= K-1 steps. Needed additional research and possible applications of this procedure are discussed.

Alpha-Max: A Novel New Multiple Comparison Procedure

Over the past several decades, methods of comparing means following a significant omnibus F test have been proposed and used to make decisions regarding pairwise and more complex comparisons. These methods have involved different philosophies on controlling Type I error. They have included methods where the Type I error rate control has been based on each individual comparison, referred to as hypothesis-wise or comparison-wise control (e.g., Fisher's Least Significant Difference Procedure or LSD) and methods where Type I error rate control has been based on an entire set of comparisons, referred to as experiment-wise or family-wise control (e.g., Tukey's Honestly Significant Difference Procedure or HSD, Bonferroni, and Scheffé). Other methods have taken stepwise approaches to controlling Type I error (e.g., Student-Newman-Keuls Procedure or SNK, Duncan's new multiple range, and variations of the Bonferroni approach). Descriptions and computational information on all of these procedures, except the variations of the Bonferroni approach, can be found in most any statistics book that includes the analysis of variance (e.g., Kirk, 1982).

In general, the most commonly used post hoc approaches have been Tukey's HSD, the Bonferroni, and the Student-Newman-Keuls. Each of these methods have their own advantages and disadvantages. While Tukey's HSD controls for experiment-wise Type I error, it is considered to be somewhat conservative. The Bonferroni, when

used for all pair-wise comparison, is also conservative, even more conservative than the HSD. The SNK is considered to have the highest power of the three, but it does not control the experiment-wise Type I error.

Because of the lack of computing availability to researchers when these methods were developed, tables of critical values were prepared to aide in their use. However, now that computing power is available on a mass scale, it is possible to consider the actual probabilities or p-values of outcomes in making decisions. Alpha-Max is a procedure that uses the actual Type I probabilities or p-values to make decisions about which pairwise differences are to be considered statistically significant. The rationale is to order the pairwise difference p-values from lowest to highest, moving from the lowest to the highest, accumulating the actual probabilities until the addition of the next higher probability exceeds the pre-set nominal alpha level. All pairwise differences whose p-values are already included in the set are considered significant, but the one(s) which result in the sum of the probabilities being higher than the a priori alpha is/are not considered to be significant. A similar procedure referred to as the sequentially rejective Bonferroni test was proposed by Holm (1979). However, in Holm's procedure, each comparison alpha for sequential test was based on a new alpha value determined as a function of the experiment-wise alpha and the step in the sequence. With the removal of this restriction, Alpha-Max increases its power in the first comparisons. The effect of this on experiment-wise Type I error is yet to be assessed, although we believe it will be in an acceptable range as compared with other competing methods.

In this research, simulated data sets are used to provide examples of the outcomes associated with this procedure compared with Bonferroni, HSD, and SNK approaches.

The purpose is to compare results from Alpha-Max with the three other approaches. It is predicted that Alpha-Max has higher power to detect differences as compared with Bonferroni and HSD, but less power to detect differences as compared with SNK. However, Alpha-Max does control the experiment-wise Type I error which SNK does not. If the sum of actual Type I probabilities in Alpha-Max is less than alpha, then Type I error cannot be higher than alpha.

Relevant Literature on Multiple Comparison Procedures

The literature on multiple comparison procedures can be divided into two primary categories: articles that propose multiple comparison procedures and articles that compare multiple comparison procedures. This review will only present literature that addresses Bonferroni procedures or compares multiple comparison procedures as this paper is primarily concerned with comparing Alpha-Max with the HSD, Bonferroni, and SNK. Both analytical and simulation methods are common techniques for comparing methods. However, most recent comparisons have been done using simulations. The most common dependent variables in the comparison have been Type I error or its probability, alpha, and power. This section reviews error rates and comparing multiple comparison procedures.

Error Rate

The most common criteria for judging multiple comparison procedures is the Type I error rate. Essentially, error rates can be defined as experiment-wise, hypothesis-wise, or somewhere in between. The error rates are related in the following manner

when the individual tests are orthogonal:

$$\alpha_{EW} = 1 - (1 - \alpha_{HW})^{C}$$

where EW = experiment-wise, HW = hypothesis-wise, and C = number of comparisons in the experiment (Ottenbacher, 1991; Toothaker, 1993). In general, the relationship can be written as an inequality also covering the cases where the individual comparisons are not orthogonal:

$$\alpha_{EW} \leq 1 - (1 - \alpha_{HW})^{C}$$

This inequality and the Bonferroni inequality (Hayes, 1988) are the basis for setting the error rates for most of the multiple comparison procedures.

Comparing Multiple Comparison Procedures

A number of studies have compared the ability of multiple comparison procedures to find significant differences (e.g., Klockars & Hancock, 1994; McCarroll, Crays, & Dunlap, 1992; McFatter & Gollob, 1986; Myette & White, 1982, March; Olejnik & Lee, 1990, April; Seaman, et al., 1989, March; Toothaker, 1993; Zwick, 1991). Results of these studies have been very consistent and suggest that procedures that control the experiment-wise error are less powerful than those that do not. Procedures that control only hypothesis-wise error rates tend to be the most powerful and procedures that use step-down procedures somewhere in between. Applying this to the three procedures examined in this study, it results in the Bonferroni being the least powerful when applied to all pairs (experiment-wise error rate), the Tukey HSD being more powerful (also experiment-wise error rate), and the SNK being the most powerful (step-down procedure), but with lowest control of Type I error..

Theoretical Rationale for Alpha-Max

The logic for Alpha-Max is rather simple. Arrange the hypotheses by p-values from the smallest to largest and accumulate the p-values until they exceed the nominal alpha. All of the hypotheses prior to the one associated with the first nonsignificant p-value are significant. Alpha can be thought of as money you have to spend on power. The most powerful way to spend this money is on comparisons that do not cost very much (i.e., have small p-values). Thus, ordering the hypotheses based on p-values from smallest to largest and buying (testing) them in that order would get you the most information for the least cost.

The theoretical rationale for Alpha-Max is equally simple. It is based on the Bonferroni inequality (Hayes, 1988, p. 411).

Alpha-Max and the Bonferroni Inequality

Simply stated, the Bonferroni inequality establishes that the experiment-wise error rate is less than or equal to the sum of the errors for the individual tests making up the experiment. Symbolically, the Bonferroni inequality is as follows:

$$\alpha_{EW} \leq \alpha_1 + \alpha_2 + \ldots + \alpha_c$$

Thus, by selecting only those tests that have error rates that sum to less than or equal to the desired experiment-wise error rate, control of the experiment-wise error rate at the desired level is assured.

This is the same rationale used with the common Bonferroni procedure except that Alpha-Max does not require one of the restrictions. The Bonferroni procedure was established by requiring that each individual test be run at the same level of significance.

Thus, α_1, α_2, through α_c were assumed to be equal to α_{HW}, the hypothesis-wise error. In this case. the Bonferroni inequality becomes:

$$\alpha_{EW} \leq \Sigma\alpha_{HW}$$

Since each hypothesis-wise α is a constant, the inequality becomes:

$$\alpha_{EW} \leq C\alpha_{HW}$$

where C is the number of individual tests that comprise the experiment. By dividing both sides of the inequality by C, it is clear that by choosing the hypothesis-wise alpha equal to the experiment-wise alpha divided by the number of tests ($\alpha_{HW} = \alpha_{EW} / C$), the desired experiment-wise alpha will be maintained.

Alpha-Max accomplishes this same result by selecting only those individual comparison alphas whose sum is less than or equal to the desired experiment-wise alpha. We have proposed an additional level of protection by requiring that Alpha-Max be preceded by a significant omnibus F test as required by Fisher when he proposed the LSD procedure.

It should be noted that the Bonferroni inequality would be an equality if the individual comparisons were independent. This is the basis for multiple comparison procedures such as the orthogonal comparison procedure and Dunnett's procedure. In cases where the individual comparisons are not independent, the Bonferroni test becomes more conservative as will the Alpha-Max procedure. Thus, based on this logic and the Bonferroni inequality, we can be assured that the experiment-wise alpha will be less than or equal to the sum of the p-values for the selected tests. If the individual tests are selected such that the sum is less than or equal to our desired experiment-wise alpha, than the experiment-wise error rate will be controlled. For example, if we choose the

experiment-wise error rate to be .05 and select the individual comparisons such that $.05 \leq \alpha_1 + \alpha_2 + ... + \alpha_C$, than the experiment-wise error rate will be less than or equal to .05.

Other Bonferroni-Type Procedures

There have been many adaptations of the basic Bonferroni procedure over the years. Most of these modified the application of the Bonferroni inequality to increase the power of the comparisons. The simplest modification was to a priori reduce the number of comparison being tested. Most of the modifications involved some type of sequential application of the Bonferroni inequality (e.g., Hochberg, 1988; Holland & Copenhaver, 1987; Holm, 1979; Hommel, 1988; Li, Olejnik, & Huberty, 1992, April; and Rom, 1990). Each of these modifications involved ordering the pair-wise comparisons based on the p-values and applying a modified alpha-value in a sequential manner. A number of articles reported comparisons among these and other multiple comparison procedures (e.g., Supattathum, Olejnik, & Li, 1994, April; de Cani, 1984; Edwards, 1991, April; Li, Olejnik, & Huberty, 1992, April; Ottenbacher, 1991). The findings tend to be that the original Bonferroni procedure is least powerful with the modified versions having varying degrees of power. However, Supattathum, Olejnik, & Li (1994, April) concluded that the increase in power over the original Bonferroni approach was not particulary high, especially when nominal alpha was .05..

Based on these studies, the Alpha-Max procedure will have as much or more power than the other procedures that are variations of the Bonferroni procedure. There may be, however, greater Type I error risk. This greater Type I error risk is due to the

non-random nature of the application of the test criteria. It is similar to using an a priori test criteria but not determining which groups to compare until after examining the differences. Only a Monte Carlo type simulation study could determine this with any degree of certainty.

Research Design and Analysis

Data Sets

Two three-group and three four-group data patterns were specified in accordance with Cohen's (1988) description of group mean patterns. Each of these was used with three group sizes, $\underline{n}$= 10, $\underline{n}$= 30, and $\underline{n}$= 100. Each data set was normally distributed and within each sample size configuration, group variances were equal.

Group Mean Patterns

Pattern 1 has one group with a low mean, one with a high mean, and all other groups with means exactly between the low and high means. This pattern has the lowest variance of the group means. Pattern 2 has all groups with means equally distant from each other. This has medium group mean variability. When there are three groups, patterns 1 and 2 are the same. Pattern 3 has half of the means at the low point and half of the means at the high point, a pattern with the highest group mean variability. When there is an odd number of groups, pattern 3 does not have an equal number of group means at the low and high points. There would be K/2-.5 at one end and K/2+.5 at the other.

Analysis

Within each group number, group size, and pattern configuration, the range of lowest and highest means was increased until a significant omnibus F statistic, at $p<.05$, was reached. In addition to the omnibus F statistic, all pairwise comparisons were tested using the original Bonferroni approach, Tukey's HSD, Student-Newman-Keuls, and Alpha-Max. The range was systematically increased by small intervals until every possible difference was detected by all four multiple comparison methods. The order in which the differences were found by each method at each step was determined and is reported in these results. All of these analyses were conducted using SPSSx, mainframe software at the University of Alabama. Alpha-Max pairwise tests were determined using weighted contrast statements and were based on pooled variance t probabilities. In addition, power was determined using the methods presented by Cohen (1988) which take into account the different patterns and omega-square was determined as the measure of strength of the among group variance.

Results

Three Group Arrangements

Pattern 1-2. In the three group situation, patterns 1 and 2 are the same. There is one low group, one in the middle, and one high group. Pattern 1-2 results for each of the sample sizes are presented in Tables 1-3. For $n = 10$ (Table 1), the omnibus F statistic was significant at 1.20σ. At this point, the largest contrast (μ_1-μ_3) was significant for all four methods. At 1.90σ, the SNK found the remaining two equally distant, pairwise differences (μ_1-μ_2 and μ_2-μ_3) significant; at 2.15σ, Alpha-Max found these

differences significant; at 2.25σ, the HSD found them different: and at 2.30σ, the Bonferroni found them significantly different.

Similar results were found for the $\underline{n}$= 30 situation (Table 2). The omnibus $\underline{F}$ was significant at 0.65σ as was the μ_1-μ_3 difference for all four methods. The remaining pairwise differences were significant using SNK at 1.05σ, using Alpha-Max at 1.20σ, using HSD at 1.25σ, and at 1.30σ for the Bonferroni. For the $\underline{n}$= 100 situation (Table 3), the omnibus $\underline{F}$ was significant at 0.35σ, where the μ_1-μ_3 contrast was found significant by all four methods. The remaining pairwise differences were significant using SNK at 0.575σ, using Alpha-Max at 0.65σ, using HSD at 0.675σ. and using Bonferroni at 0.70σ.

Pattern 3. Results for Pattern 3, all means at the extremes, are presented in Tables 4-6. In this case, the means for groups 1 and 2 were the same at the low end compared with the mean of group 3 at the high end of the range. In this pattern, there are only two possible differences, μ_1-μ_3 and μ_2-μ_3. As such, the highest difference is the only difference and it occurs twice. Thus, there are two differences tied at $\underline{r}$= 3 steps for the SNK. Because of random variation, this is unlikely to actually occur in real data situations. For this analysis, they will both be treated as being significantly different at the highest number of steps.

For the $\underline{n}$= 10 situation (Table 4), the omnibus $\underline{F}$ was significant at 1.01σ. At this point, both differences were considered significant using the SNK. At 1.07σ, Alpha-Max found the differences significant, they were found different at 1.11σ using HSD, and at 1.15σ using Bonferroni. For the $\underline{n}$= 30 situation (Table 5), results were very similar. The omnibus $\underline{F}$ was significant and both pairwise differences significant using SNK at 0.56σ. At 0.59σ, Alpha-Max found both significant; at 0.62σ, HSD found them

significant; and at 0.64σ, the Bonferroni found the differences significant. For n= 100 situation (Table 6), the omnibus F and SNK differences were found at 0.305σ. At 0.32σ, Alpha-Max found the differences; at 0.335σ, differences were determined by HSD; and at 0.345σ, differences were found using the Bonferroni approach.

In every three-group pattern situation, across all three sample sizes, SNK detected significant differences first, Alpha-Max detected significant differences second, followed by HSD third, and lastly by Bonferroni.

Four Group Arrangements

Pattern 1. Four-group, pattern 1 mean comparisons are reported in Tables 7-9. In this case the largest mean difference is the r= 4 step case, with the contrast of μ_1-μ_4. Since the two means in the middle (μ_2 and μ_3) are the same, the μ_2-μ_3 contrast is zero. The other four contrasts are equal in mean difference. These are: μ_1-μ_2, μ_1-μ_3, μ_2-μ_4, and μ_3-μ_4. Table 7 presents the results for the n= 10 situation. At 1.35σ, the omnibus F was significant and the μ_1-μ_4 difference was found to be significant by all four methods. At 1.90σ, SNK found the other four mean differences significant. At 2.36σ, Alpha-Max found these differences significant; at 2.44σ, HSD found the differences significant; and at 2.50σ, Bonferroni found the differences significant.

The same orders of difference were found with the n= 30 and n= 100 situations. In the n= 30 situation (Table 8), the omnibus F and the μ_1-μ_4 difference was found at 0.75σ. The other four pairwise differences were found by SNK at 1.05σ, by Alpha-Max at 1.32σ, by HSD at 1.35σ, and by Bonferroni at 1.40σ. In the n= 100 situation (Table 9), the omnibus F and the μ_1-μ_4 difference was found at 0.40σ. The other four pairwise

differences were found by SNK at 0.575σ, by Alpha-Max at 0.71σ, by HSD at 0.74σ, and by Bonferroni at 0.75σ. In all three, four-group, pattern 1 sample size situations, SNK found the differences first, Alpha-Max was second, followed by the HSD and Bonferroni.

Pattern 2. In the four group, pattern 2 situation the means are equally spaced across the range of means. There is one r= 4 step mean difference which is represented by the μ_1-μ_4 contrast. There are two r= 3 step mean contrasts (μ_1-μ_3 and μ_2-μ_4) and three r= 2 step mean contrasts (μ_1-μ_2, μ_2-μ_3, and μ_3-μ_4). Results for the three sample size configurations are presented in Tables 10-12. In the n= 10 situation (Table 10), the omnibus F was significant at 1.30σ. All four methods found the μ_1-μ_4 contrast significant at this point. The two r= 3 step differences were found significant first by Alpha-Max at 1.60σ, followed by SNK at 1.70σ. HSD found the r= 3 contrasts significant at 1.85σ and Bonferroni found them significant at 1.90σ. Relative to the three r= 2 contrasts, SNK found them significant at 2.80σ, Alpha-Max found them significant at 3.40σ, HSD found them significant at 3.70σ, and Bonferroni found them significant at 3.80σ.

For the n= 30 situation (Table 11) the omnibus F and the μ_1-μ_4 difference were found significant by all four methods at 0.70σ. The two r= 3 step means were found significant at 0.90σ by Alpha-Max. SNK found these differences significant at 0.95σ, HSD found them significant at 1.02σ, and Bonferroni found them significant at 1.05σ. The remaining three pairwise differences were found significant by SNK at 1.55σ, by Alpha-Max at 1.90σ, by HSD at 2.05σ, and by Bonferroni at 2.10σ. Very similar results were observed for the n= 100 situation (Table 12). The omnibus F and the r= 4 step contrast were significant at 0.40σ. The two r= 3 step mean differences were found significant at 0.50σ by Alpha-Max. SNK found these differences significant at 0.52σ,

HSD found them significant at 0.55σ, and Bonferroni found them significant at 0.60σ. The remaining three pairwise differences were found significant by SNK at 0.85σ, by Alpha-Max at 1.05σ, by HSD at 1.10σ, and by Bonferroni at 1.15σ.

In all three four group, pattern 2 situations, Alpha-Max detected the $\underline{r}= 3$ step mean differences before all other methods including SNK. However, at the $\underline{r}= 2$ step mean differences the order of Alpha-Max and SNK detection were reversed. Both Alpha-Max and SNK detected all differences before HSD and Bonferroni. It may be that this is a group mean configuration where Alpha-Max is clearly preferable to all of the other methods in detecting the mean differences at $\underline{r}=$ K-1 steps, and perhaps at other higher or lower steps when K is large.

Pattern 3. In the four group, pattern 3 situation two means are tied at the low mean value and two tied at the high mean value. Results for comparing all pairwise differences for the three sample size configurations having this pattern are found in Tables 13-15. With this pattern, there are four mean difference contrasts that are tied at the same difference: μ_1-μ_3, μ_1-μ_4, μ_2-μ_3, μ_2-μ_4. Due to random variation, in a typical real data situation, this situation is not likely to happen.

In the $\underline{n}= 10$ situation, presented in Table 13, the omnibus $\underline{F}$ was found significant at 0.95σ. At this point the tied four contrasts were found different with SNK. Alpha-Max found these four contrasts significant at 1.20σ, HSD found them significant at 1.22σ, and Bonferroni found them significant at 1.25σ. Results for the $\underline{n}= 30$ and $\underline{n}=$ 100 situations were very similar. As indicated in Table 14, the omnibus $\underline{F}$ and the SNK tied differences were found significant at 0.53σ. Alpha-Max found the four pairwise contrasts significant at 0.66σ, HSD found the differences at 0.68σ, and Bonferroni found

the differences significant at 0.70σ. Table 15 presents results for the $\underline{n}$= 100 situation. The omnibus $\underline{F}$ and the SNK tied differences were found significant at 0.29σ. Alpha-Max found the four pairwise contrasts significant at 0.36σ, HSD found the differences significant at 0.37σ, and Bonferroni found the differences significant at 0.38σ.

While it appears the SNK is much more powerful in this case, that would not be the case if the means were not tied. Actually, one of these mean differences would be at the $\underline{r}$= 2 level. The Alpha-Max, HSD, and Bonferroni methods found differences at about the same range value. However, if the means were not tied, Alpha-Max would likely have detected differences at much lower range values as compared to HSD and Bonferroni.

Conclusions

In every case studied, Alpha-Max was more powerful than HSD and Bonferroni. For patterns 1 and 2, all methods detected the largest difference at the same point as the omnibus $\underline{F}$ statistic being determined as significant. In the pattern 2 case, at the K-1 steps, Alpha-Max is more powerful than all of the methods compared including SNK. At the $\underline{r}$= 2 step situation, SNK is the most powerful, followed by Alpha-Max, HSD, and Bonferroni. However, at this level SNK is recognized as not having desirable control of Type I error rate. In the perfect status of the pattern 3 situation, SNK is clearly the most powerful and the other three methods are very close relative to power. Random variations around this pattern are likely to show Alpha-Max to have clearly higher power than the HSD and Bonferroni.

While these results indicate that Alpha-Max has potential of providing a more

powerful alternative to HSD and Bonferroni in every case and higher than SNK in the pattern 2 case and a method with more desirable control of Type I error as compared with SNK, there is another very strong advantage to Alpha-Max. It is highly flexible. The only requirement for its use is being able to determine the contrast probabilities, which is easily done with current microcomputer and mainframe software. Thus, it could be used for nonparametric as well as parametric multiple comparisons. It could be used with nonorthogonal, planned comparisons as an alternative to the Bonferroni. It has promise for being able to test contrasts in the lack of homogeneity of variance situation as well.

A promising application of the Alpha-Max Procedure is as an a priori multiple comparison procedure. To use it is this way, the first step is to put the hypotheses in priority order. After the p-value associated with each hypothesis is obtained, begin accumulating the p-values as before. All hypotheses are significant as long as the sum of the accumulated p-values is less than or equal to the desired experiment-wise alpha. Applying Alpha-Max in this way will eliminate the possibility of a slightly inflated experiment-wise error rate. It also is in keeping with the advice of many researchers (e.g., Thompson, 1990, April; Wang, 1993, November) who recommend using a priori multiple comparisons.

Future Research

At this point, we have proposed Alpha-Max as a new approach to conducting multiple comparisons. While the use of simulated group mean patterns with varying sample sizes has demonstrated that Alpha-Max is at least as powerful as Tuky's HSD and

Bonferroni, and in some cases more powerful than SNK, there is still a need to conduct more extensive research on this method. The primary need is to empirically establish, through use of Monte Carlo studies, actual Type I error rates in the various applications of Alpha-Max. Another need is to compare Alpha-Max results with those from the modifications of the Bonferroni procedure. If these studies conclude that Alpha-Max has as good or better control of Type I error, then applications should be examined.

Future studies should examine applications of Alpha-Max in situations of: lack of homogeneity where p-values based on separate variance could be used with Alpha-Max; its use as a nonparametric multiple comparison procedure; its use in nonorthogonal, planned procedures; its use with directional tests (even different directions on some contrasts compared with others) in orthogonal or nonorthogonal planned comparisons; its use as an alternative to Dunnett's tests for comparing groups with a predetermined control group; and its use in followup of interaction cell means.

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Table 1

Significant Pairwise Differences for Four Post-hoc Methods,

K = 3, Pattern 1-2, n = 10, $\alpha = 0.05$

	Range	1.20σ	1.90σ	2.15σ	2.25σ	2.30σ
	F Pr > F	3.60 .0411	9.03 .0010	11.56 .0002	12.66 .0001	13.23 .0001
	Power	.62	.96	.99	.99+	.99+
	ω^2	.148	.349	.413	.437	.449
Procedure	**Contrast**					
Bonferroni	μ_1-μ_3 μ_1-μ_2 μ_2-μ_3	*	*	*	*	* * *
Tukey's HSD	μ_1-μ_3 μ_1-μ_2 μ_2-μ_3	*	*	*	* * *	* * *
Alpha-Max with Type I Probabilities	μ_1-μ_3 μ_1-μ_2 μ_2-μ_3	.012* .191 .191	.000* .043 .043	.000* .023* .023*	.000* .018* .018*	.000* .016* .016*
Student Newman-Keuls	μ_1-μ_3 μ_1-μ_2 μ_2-μ_3	*	* * *	* * *	* * *	* * *

* Significant contrast at $p < .05$.

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Table 2

Significant Pairwise Differences for Four Post-hoc Methods,

$K = 3$, Pattern 1-2, $n = 30$, $\alpha = 0.05$

	Range	0.65σ	1.05σ	1.20σ	1.25σ	1.30σ
	F Pr>F	3.17 .0470	8.27 .0005	10.80 .0001	11.72 .0000	12.68 .0000
	Power	.60	.95	.98	.99	.99+
	ω^2	.046	.139	.179	.192	.206
Procedure	Contrast					
Bonferroni	μ_1-μ_3 μ_1-μ_2 μ_2-μ_3	*	*	*	*	* * *
Tukey's HSD	μ_1-μ_3 μ_1-μ_2 μ_2-μ_3	*	*	*	* * *	* * *
Alpha-Max with Type I Probabilities	μ_1-μ_3 μ_1-μ_2 μ_2-μ_3	.014* .211 .211	.000* .045 .045	.000* .022* .022*	.000* .018* .018*	.000* .014* .014*
Student Newman-Keuls	μ_1-μ_3 μ_1-μ_2 μ_2-μ_3	*	* * *	* * *	* * *	* * *

* Significant contrast at $p < .05$.

Table 3

Significant Pairwise Differences for Four Post-hoc Methods,

K= 3, Pattern 1-2, n= 100, α= 0.05

	Range	$.350\sigma$	$.575\sigma$	$.650\sigma$	$.675\sigma$	$.700\sigma$
	F Pr>F	3.06 .0483	8.27 .0003	10.56 .0000	11.39 .0000	12.25 .0000
	Power	.59	.95	.99	.99+	.99+
	ω^2	.017	.046	.060	.065	.070
Procedure	**Contrast**					
Bonferroni	μ_1-μ_3 μ_1-μ_2 μ_2-μ_3	*	*	*	*	* * *
Tukey's HSD	μ_1-μ_3 μ_1-μ_2 μ_2-μ_3	*	*	*	* * *	* * *
Alpha-Max with Type I Probabilities	μ_1-μ_3 μ_1-μ_2 μ_2-μ_3	.014* .217 .217	.000* .043 .043	.000* .022* .022*	.000* .018* .018*	.000* .014* .014*
Student Newman-Keuls	μ_1-μ_3 μ_1-μ_2 μ_2-μ_3	*	* * *	* * *	* * *	* * *

* **Significant contrast at** $p<.05$.

Table 4

Significant Pairwise Differences for Four Post-hoc Methods,

K= 3, Pattern= 3, n= 10, α= 0.05

	Range	1.01σ	1.07σ	1.11σ	1.15σ
	F Pr>F	3.40 .0482	3.82 .0347	4.11 .0277	4.41 .0220
	Power	.59	.65	.68	.71
	ω^2	.138	.158	.172	.185
Procedure	**Contrast**				
Bonferroni	μ_1-μ_3 μ_2-μ_3 μ_1-μ_2				* *
Tukey's HSD	μ_1-μ_3 μ_2-μ_3 μ_1-μ_2			* *	* *
Alpha-Max with Type I Probabilities	μ_1-μ_3 μ_2-μ_3 μ_1-μ_2	.032 .032 1.00	.024* .024* 1.00	.020* .020* 1.00	.016* .016* 1.00
Student-Newman-Keuls	μ_1-μ_3 μ_2-μ_3 μ_1-μ_2	(*) (*)	(*) (*)	(*) (*)	(*) (*)

* Significant contrast at $p<.05$.
(*) SNK differences tied at r= 3 steps.

Table 5

Significant Pairwise Differences for Four Post-hoc Methods,

K= 3, Pattern= 3, n= 30, α= 0.05

	Range	0.56σ	0.59σ	0.62σ	0.64σ
	F Pr>F	3.14 .0484	3.48 .0351	3.84 .0251	4.10 .0200
	Power	.59	.64	.68	.71
	ω^2	.045	.052	.059	.064
Procedure	Contrast				
Bonferroni	μ_1-μ_3 μ_2-μ_3 μ_1-μ_2				* *
Tukey's HSD	μ_1-μ_3 μ_2-μ_3 μ_1-μ_2			* *	* *
Alpha-Max with Type I Probabilities	μ_1-μ_3 μ_2-μ_3 μ_1-μ_2	.033 .033 1.00	.025* .025* 1.00	.018* .018* 1.00	.015* .015* 1.00
Student-Newman-Keuls	μ_1-μ_3 μ_2-μ_3 μ_1-μ_2	(*) (*)	(*) (*)	(*) (*)	(*) (*)

* Significant contrast at $p<.05$.

(*) SNK differences tied at r= 3 steps.

Table 6

Significant Pairwise Differences for Four Post-hoc Methods,

K= 3, Pattern= 3, n= 100, α= 0.05

	Range	.305σ	.320σ	.335σ	.345σ
	F Pr>F	3.10 .0465	3.41 .0342	3.74 .0249	3.97 .0199
	Power	.60	.64	.68	.70
	ω^2	.014	.016	.018	.019
Procedure	Contrast				
Bonferroni	μ_1-μ_3 μ_2-μ_3 μ_1-μ_2				* *
Tukey's HSD	μ_1-μ_3 μ_2-μ_3 μ_1-μ_2			* *	* *
Alpha-Max with Type I Probabilities	μ_1-μ_3 μ_2-μ_3 μ_1-μ_2	.032 .032 1.00	.024* .024* 1.00	.018* .018* 1.00	.015* .015* 1.00
Student-Newman-Keuls	μ_1-μ_3 μ_2-μ_3 μ_1-μ_2	(*) (*)	(*) (*)	(*) (*)	(*) (*)

* Significant contrast at $p < .05$.
(*) SNK differences tied at r= 3 steps.

Table 7

Significant Pairwise Differences for Four Post-hoc Methods,

K= 4, Pattern 1, n= 10, α= 0.05

	Range	1.35σ	1.90σ	2.36σ	2.44σ	2.50σ
	F Pr>F	3.04 .0414	6.02 .0020	9.28 .0001	9.92 .0001	10.42 .0000
	Power	.67	.94	.99+	.99+	.99+
	ω^2	.133	.273	.383	.401	.414
Procedure	**Contrast**					
Bonferroni	μ_1-μ_4	*	*	*	*	*
	μ_1-μ_3					*
	μ_2-μ_4					*
	μ_1-μ_2					*
	μ_3-μ_4					*
	μ_2-μ_3					
Tukey's HSD	μ_1-μ_4	*	*	*	*	*
	μ_1-μ_3				*	*
	μ_2-μ_4				*	*
	μ_1-μ_2				*	*
	μ_3-μ_4				*	*
	μ_2-μ_3					
Alpha-Max with Type I Probabilities	μ_1-μ_4	.005*	.000*	.000*	.000*	.000*
	μ_1-μ_3	.140	.041	.012*	.010*	.008*
	μ_2-μ_4	.140	.041	.012*	.010*	.008*
	μ_1-μ_2	.140	.041	.012*	.010*	.008*
	μ_3-μ_4	.140	.041	.012*	.010*	.008*
	μ_2-μ_3	1.00	1.00	1.00	1.00	1.00
Student Newman-Keuls	μ_1-μ_4	*	*	*	*	*
	μ_1-μ_3		(*)	(*)	(*)	(*)
	μ_2-μ_4		(*)	(*)	(*)	(*)
	μ_1-μ_2		(*)	(*)	(*)	(*)
	μ_3-μ_4		(*)	(*)	(*)	(*)
	μ_2-μ_3					

* Significant contrast at $p<.05$.

(*) SNK differences tied at r= 3 steps.

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Table 8

Significant Pairwise Differences for Four Post-hoc Methods,

K= 4, Pattern 1, n= 30, α= 0.05

	Range	0.75σ	1.05σ	1.32σ	1.35σ	1.40σ
	F Pr>F	2.81 .0424	5.51 .0014	8.71 .0000	9.11 .0000	9.80 .0000
	Power	.67	.93	.98	.98	.99+
	ω^2	.043	.101	.162	.169	.180
Procedure	**Contrast**					
Bonferroni	μ_1-μ_4	*	*	*	*	*
	μ_1-μ_3					*
	μ_2-μ_4					*
	μ_1-μ_2					*
	μ_3-μ_4					*
	μ_2-μ_3					
Tukey's HSD	μ_1-μ_4	*	*	*	*	*
	μ_1-μ_3				*	*
	μ_2-μ_4				*	*
	μ_1-μ_2				*	*
	μ_3-μ_4				*	*
	μ_2-μ_3					
Alpha-Max with Type I Probabilities	μ_1-μ_4	.004*	.000*	.000*	.000*	.000*
	μ_1-μ_3	.149	.044	.012*	.010*	.008*
	μ_2-μ_4	.149	.044	.012*	.010*	.008*
	μ_1-μ_2	.149	.044	.012*	.010*	.008*
	μ_3-μ_4	.149	.044	.012*	.010*	.008*
	μ_2-μ_3	1.00	1.00	1.00	1.00	1.00
Student-Newman-Keuls	μ_1-μ_4	*	*	*	*	*
	μ_1-μ_3		(*)	(*)	(*)	(*)
	μ_2-μ_4		(*)	(*)	(*)	(*)
	μ_1-μ_2		(*)	(*)	(*)	(*)
	μ_3-μ_4		(*)	(*)	(*)	(*)
	μ_2-μ_3					

* Significant contrast at $p < .05$.

(*) SNK differences tied at r= 3 steps.

Table 9

Significant Pairwise Differences for Four Post-hoc Methods,

K= 4, Pattern 1, n= 100, α= 0.05

	Range	$.400\sigma$	$.575\sigma$	$.710\sigma$	$.740\sigma$	$.750\sigma$
	F Pr>F	2.67 .0475	5.51 .0010	8.40 .0000	9.13 .0000	9.38 .0000
	Power	.65	.93	.99+	.99+	.99+
	ω^2	.012	.033	.053	.057	.059
Procedure	**Contrast**					
Bonferroni	μ_1-μ_4	*	*	*	*	*
	μ_1-μ_3					*
	μ_2-μ_4					*
	μ_1-μ_2					*
	μ_3-μ_4					*
	μ_2-μ_3					
Tukey's HSD	μ_1-μ_4	*	*	*	*	*
	μ_1-μ_3				*	*
	μ_2-μ_4				*	*
	μ_1-μ_2				*	*
	μ_3-μ_4				*	*
	μ_2-μ_3					
Alpha-Max with Type I Probabilities	μ_1-μ_4	.005*	.000*	.000*	.000*	.000*
	μ_1-μ_3	.158	.043	.012*	.009*	.008*
	μ_2-μ_4	.158	.043	.012*	.009*	.008*
	μ_1-μ_2	.158	.043	.012*	.009*	.008*
	μ_3-μ_4	.158	.043	.012*	.009*	.008*
	μ_2-μ_3	1.00	1.00	1.00	1.00	1.00
Student-Newman-Keuls	μ_1-μ_4	*	*	*	*	*
	μ_1-μ_3		(*)	(*)	(*)	(*)
	μ_2-μ_4		(*)	(*)	(*)	(*)
	μ_1-μ_2		(*)	(*)	(*)	(*)
	μ_3-μ_4		(*)	(*)	(*)	(*)
	μ_2-μ_3					

* Significant contrast at $p < .05$.

(*) SNK differences tied at r= 3 level.

Table 10

Significant Pairwise Differences for Four Post-hoc Methods,

K= 4, Pattern 2, n= 10, α= 0.05

	Range	1.30σ	1.60σ	1.70σ	1.85σ	1.90σ	2.80σ	3.40σ	3.70σ	3.80σ
	F	3.13	4.74	5.35	6.34	6.69	14.52	21.41	25.35	26.74
	Pr>F	.0375	.0069	.0038	.0015	.0011	.0000	.0000	.0000	.0000
	Power	.68	.87	.90	.95	.96	.99+	.99+	.99+	.99+
	ω^2	.138	.219	.246	.286	.299	.503	.605	.646	.654
Procedure	Contrast									
Bonferroni	μ_1-μ_4	*	*	*	*	*	*	*	*	*
	μ_1-μ_3					*	*	*	*	*
	μ_2-μ_4					*	*	*	*	*
	μ_1-μ_2									*
	μ_2-μ_3									*
	μ_3-μ_4									*
Tukey's HSD	μ_1-μ_4	*	*	*	*	*	*	*	*	*
	μ_1-μ_3				*	*	*	*	*	*
	μ_2-μ_4				*	*	*	*	*	*
	μ_1-μ_2								*	*
	μ_2-μ_3								*	*
	μ_3-μ_4								*	*
Alpha-Max with Type I Probabilities	μ_1-μ_4	.006*	.001*	.001*	.000*	.000*	.000*	.000*	.000*	.000*.
	μ_1-μ_3	.061	.022*	.016*	.009*	.008*	.000*	.000*	.000*	000*
	μ_2-μ_4	.061	.022*	.016*	.009*	.008*	.000*	.000*	.000*	.000*
	μ_1-μ_2	.339	.241	.213	.176	.165	.044	.016*	.009*	.008*
	μ_2-μ_3	.339	.241	.213	.176	.165	.044	.016*	.009*	.008*
	μ_3-μ_4	.339	.241	.213	.176	.165	.044	.016*	.009*	.008*
Student-Newman-Keuls	μ_1-μ_4	*	*	*	*	*	*	*	*	*
	μ_1-μ_3			*	*	*	*	*	*	*
	μ_2-μ_4			*	*	*	*	*	*	*
	μ_1-μ_2						*	*	*	*
	μ_2-μ_3						*	*	*	*
	μ_3-μ_4						*	*	*	*

* Significant contrast at $p<.05$.

Table 11

Significant Pairwise Differences for Four Post-hoc Methods,

K= 4, Pattern 2, n= 30, α= 0.05

	Range	0.70σ	0.90σ	0.95σ	1.02σ	1.05σ	1.55σ	1.90σ	2.05σ	2.10σ
	F	2.72	4.50	5.01	5.78	6.13	13.35	20.06	23.35	24.50
	Pr > F	.0476	.0050	.0026	.0010	.0007	.0000	.0000	.0000	.0000
	Power	.65	.87	.91	.94	.95	.99+	.99+	.99+	.99+
	ω^2	.041	.080	.091	.107	.114	.236	.323	.358	.370
Procedure	Contrast									
Bonferroni	$\mu_1-\mu_4$	*	*	*	*	*	*	*	*	*
	$\mu_1-\mu_3$					*	*	*	*	*
	$\mu_2-\mu_4$					*	*	*	*	*
	$\mu_1-\mu_2$									*
	$\mu_2-\mu_3$									*
	$\mu_3-\mu_4$									*
Tukey's HSD	$\mu_1-\mu_4$	*	*	*	*	*	*	*	*	*
	$\mu_1-\mu_3$				*	*	*	*	*	*
	$\mu_2-\mu_4$				*	*	*	*	*	*
	$\mu_1-\mu_2$								*	*
	$\mu_2-\mu_3$								*	*
	$\mu_3-\mu_4$								*	*
Alpha-Max with Type I Probabilities	$\mu_1-\mu_4$	.008*	.001*	.000*	.000*	.000*	.000*	.000*	.000*	.000*
	$\mu_1-\mu_3$	.073	.022*	.016*	.010*	.008*	.000*	.000*	.000*	.000*
	$\mu_2-\mu_4$	.073	.022*	.016*	.010*	.008*	.000*	.000*	.000*	.000*
	$\mu_1-\mu_2$	.368	.248	.223	.190	.178	.048	.016*	.009*	.008*
	$\mu_2-\mu_3$	.368	.248	.223	.190	.178	.048	.016*	.009*	.008*
	$\mu_3-\mu_4$	.368	.248	.223	.190	.178	.048	.016*	.009*	.008*
Student-Newman-Keuls	$\mu_1-\mu_4$	*	*	*	*	*	*	*	*	*
	$\mu_1-\mu_3$			*	*	*	*	*	*	*
	$\mu_2-\mu_4$			*	*	*	*	*	*	*
	$\mu_1-\mu_2$						*	*	*	*
	$\mu_2-\mu_3$						*	*	*	*
	$\mu_3-\mu_4$						*	*	*	*

* Significant contrast at $p < .05$.

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Table 12

Significant Pairwise Differences for Four Post-hoc Methods,

K = 4, Pattern 2, n = 100, $\alpha = 0.05$

	Range	0.40σ	0.50σ	0.52σ	0.55σ	0.60σ	0.85σ	1.05σ	1.10σ	1.15σ
	F	2.96	4.63	5.01	5.60	6.67	13.38	20.42	22.41	24.49
	Pr > F	.0320	.0034	.0020	.0009	.0002	.0000	.0000	.0000	.0000
	Power	.70	.87	.90	.94	.96	.99+	.99+	.99+	.99+
	ω^2	.019	.035	.038	.044	.053	.110	.162	.176	.190
Procedure	**Contrast**									
Bonferroni	μ_1-μ_4	*	*	*	*	*	*	*	*	*
	μ_1-μ_3					*	*	*	*	*
	μ_2-μ_4					*	*	*	*	*
	μ_1-μ_2									*
	μ_2-μ_3									*
	μ_3-μ_4									*
Tukey's HSD	μ_1-μ_4	*	*	*	*	*	*	*	*	*
	μ_1-μ_3				*	*	*	*	*	*
	μ_2-μ_4				*	*	*	*	*	*
	μ_1-μ_2								*	*
	μ_2-μ_3								*	*
	μ_3-μ_4								*	*
Alpha-Max with Type I Probabilities	μ_1-μ_4	.005*	.000*	.000*	.000*	.000*	.000*	.000*	.000*	.000*
	μ_1-μ_3	.060	.019*	.015*	.010*	.005*	.000*	.000*	.000*	.000*
	μ_2-μ_4	.060	.019*	.015*	.010*	.005*	.000*	.000*	.000*	.000*
	μ_1-μ_2	.346	.239	.221	.196	.158	.046	.014*	.010*	.007*
	μ_2-μ_3	.346	.239	.221	.196	.158	.046	.014*	.010*	.007*
	μ_3-μ_4	.346	.239	.221	.196	.158	.046	.014*	.010*	.007*
Student-Newman-Keuls	μ_1-μ_4	*	*	*	*	*	*	*	*	*
	μ_1-μ_3			*	*	*	*	*	*	*
	μ_2-μ_4			*	*	*	*	*	*	*
	μ_1-μ_2						*	*	*	*
	μ_2-μ_3						*	*	*	*
	μ_3-μ_4						*	*	*	*

* Significant contrast at $p < .05$.

Table 13

Significant Pairwise Differences for Four Post-hoc Methods,

K= 4, Pattern 3, n= 10, α= 0.05

	Range	.95σ	1.20σ	1.22σ	1.25σ
	F Pr>F	3.01 .0428	4.80 .0065	4.96 .0055	5.21 .0043
	Power	.66	.87	.88	.89
	ω^2	.131	.222	.229	.240
Procedure	Contrast				
Bonferroni	μ_1-μ_3				*
	μ_1-μ_4				*
	μ_2-μ_3				*
	μ_2-μ_4				*
	μ_1-μ_2				
	μ_3-μ_4				
Tukey's HSD	μ_1-μ_3			*	*
	μ_1-μ_4			*	*
	μ_2-μ_3			*	*
	μ_2-μ_4			*	*
	μ_1-μ_2				
	μ_3-μ_4				
Alpha-Max with Type I Probabilities	μ_1-μ_3	.041	.011*	.010*	.008*
	μ_1-μ_4	.041	.011*	.010*	.008*
	μ_2-μ_3	.041	.011*	.010*	.008*
	μ_2-μ_4	.041	.011*	.010*	.008*
	μ_1-μ_2	1.00	1.00	1.00	1.00
	μ_3-μ_4	1.00	1.00	1.00	1.00
Student-Newman-Keuls	μ_1-μ_3	(*)	(*)	(*)	(*)
	μ_1-μ_4	(*)	(*)	(*)	(*)
	μ_2-μ_3	(*)	(*)	(*)	(*)
	μ_2-μ_4	(*)	(*)	(*)	(*)
	μ_1-μ_2				
	μ_3-μ_4				

* Significant contrast at $p<.05$.

(*) SNK differences tied at r= 4 steps.

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Table 14

Significant Pairwise Differences for Four Post-hoc Methods,

K= 4, Pattern 3, n= 30, α= 0.05

	Range	0.53σ	0.66σ	0.68σ	0.70σ
	F Pr > F	2.81 .0426	4.36 .0060	4.62 .0043	4.90 .0030
	Power	.66	.86	.88	.90
	ω^2	.043	.077	.083	.089
Procedure	**Contrast**				
Bonferroni	μ_1-μ_3				*
	μ_1-μ_4				*
	μ_2-μ_3				*
	μ_2-μ_4				*
	μ_1-μ_2				
	μ_3-μ_4				
Tukey's HSD	μ_1-μ_3			*	*
	μ_1-μ_4			*	*
	μ_2-μ_3			*	*
	μ_2-μ_4			*	*
	μ_1-μ_2				
	μ_3-μ_4				
Alpha-Max with Type I Probabilities	μ_1-μ_3	.042	.012*	.010*	.008*
	μ_1-μ_4	.042	.012*	.010*	.008*
	μ_2-μ_3	.042	.012*	.010*	.008*
	μ_2-μ_4	.042	.012*	.010*	.008*
	μ_1-μ_2	1.00	1.00	1.00	1.00
	μ_3-μ_4	1.00	1.00	1.00	1.00
Student-Newman-Keuls	μ_1-μ_3	(*)	(*)	(*)	(*)
	μ_1-μ_4	(*)	(*)	(*)	(*)
	μ_2-μ_3	(*)	(*)	(*)	(*)
	μ_2-μ_4	(*)	(*)	(*)	(*)
	μ_1-μ_2				
	μ_3-μ_4				

* Significant contrast at $p < .05$.

(*) SNK differences tied at r= 4 steps.

Table 15

Significant Pairwise Differences for Four Post-hoc Methods,

$K = 4$, Pattern 3, $n = 100$, $\alpha = 0.05$

	Range	0.29σ	0.36σ	0.37σ	0.38σ
	F Pr>F	2.80 .0396	4.32 .0052	4.56 .0037	4.81 .0026
	Power	.68	.84	.86	.89
	ω^2	.013	.024	.026	.028
Procedure	Contrast				
Bonferroni	$\mu_1-\mu_3$ $\mu_1-\mu_4$ $\mu_2-\mu_3$ $\mu_2-\mu_4$ $\mu_1-\mu_2$ $\mu_3-\mu_4$				* * * *
Tukey's HSD	$\mu_1-\mu_3$ $\mu_1-\mu_4$ $\mu_2-\mu_3$ $\mu_2-\mu_4$ $\mu_1-\mu_2$ $\mu_3-\mu_4$			* * * *	* * * *
Alpha-Max with Type I Probabilities	$\mu_1-\mu_3$ $\mu_1-\mu_4$ $\mu_2-\mu_3$ $\mu_2-\mu_4$ $\mu_1-\mu_2$ $\mu_3-\mu_4$	.041 .041 .041 .041 1.00 1.00	.011* .011* .011* .011* 1.00 1.00	.009* .009* .009* .009* 1.00 1.00	.008* .008* .008* .008* 1.00 1.00
Student-Newman-Keuls	$\mu_1-\mu_3$ $\mu_1-\mu_4$ $\mu_2-\mu_3$ $\mu_2-\mu_4$ $\mu_1-\mu_2$ $\mu_3-\mu_4$	(*) (*) (*) (*)	(*) (*) (*) (*)	(*) (*) (*) (*)	(*) (*) (*) (*)

* Significant contrast at $p < .05$.

(*) SNK differences tied at $r = 4$ steps.

TM026287

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